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WHAT IS LIFE? AMONG OTHER THINGS, IT'S A SYNERGISTIC EFFECT!

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ABSTRACT: There have been many different ways of characterizing and describing the phenomenon of life over the years. One aspect that has not often been stressed is life's emergent properties—the synergies that are produced when many elements or parts combine to produce distinctive new "wholes". Indeed, complex living systems represent a multi-leveled, multi-faceted hierarchy of synergistic effects that has evolved over several billion years. Some of the many examples of synergy at various levels of life are briefly described, and it is emphasized that life is still creating itself and still exploring its potentialities.

KEYWORDS: Synergy; Emergence; Evolution; Symbiosis; Hierarchy

Of all the wonders of the universe, life is surely the most wonderful. And complex. For living organisms have many unique attributes. Perhaps this is what accounts for our persistent difficulty in being able to define it in any succinct and quintessential way.

Over the years, life has been variously characterized as a "happening", a thermodynamic process, a repository (and a user) of information, a mind-boggling array of chemical processes, a complex division of labor, a robot vehicle designed to further the interests of "selfish genes," and many others. Life has also been clothed with various portentous buzzwords—autopoeisis, emergence, self-organization, sentience, autonomy, and more. And, of course, generations of philosophers and humanists, from Plato and Aristotle in ancient Greece to the 20th century paleontologist/priest Pierre Teilhard de Chardin—and many others before and since—have pondered the remarkable phenomenon of life in an effort to illuminate its essence.

We can perhaps date the entry of the scientific community into this dialogue to the Nobel physicist Erwin Schrödinger's legendary book "*What is Life?*" (1945), which was based on a set of his wartime lectures in Ireland. However, Schrödinger did not attempt to explore this ultimate question from a broad perspective. Rather, he advanced a reductionist claim about what he considered to be the most important physical property of life – its thermodynamic foundation. As a scientist with an interest in thermodynamics and the Second Law, which seemed to imply that there is a general trend in the universe toward energy dissipation (entropy) and an ultimate "heat death," Schrödinger posited the existence of a counteracting trend in living systems which he called "negative entropy." Living systems are distinctive in that they create thermodynamic order, he observed. Shrödinger's one-dimensional viewpoint subsequently evoked much debate (see especially the critique in Corning and Kline 1968a,b). Nevertheless, his vision remains a pioneering effort to undergird our view of life within a scientific framework.

This naturalistic approach to understanding living systems flourished in the years after World War Two, when scientists began to address the concrete questions of how life originated and how it developed the capacity to reproduce itself. Stanley Miller's famous experiments in which amino acids were produced in a laboratory, James Watson and Francis Crick's breakthrough discovery of the double helix and the role of DNA in heredity, and a vast outpouring of work in many sub-disciplines of biology in the half-century since have greatly enriched our understanding of the physical and chemical properties of living systems. It now seems evident that life can and did arise out of the raw materials and synthetic processes that were readily available in the natural world at that time, perhaps even in an environment that was quite hostile to our own aerobic form of life. So, even if, in accordance with the so-called anthropic argument, the origins of life required a rare concatenation of improbable preconditions, it is not necessary to invoke a miraculous event.

Some scientists, especially those with a reductionist orientation, firmly believe that a full, complete physical/biological explanation of life will eventually emerge from our ongoing scientific investigations. Biologist Edward Wilson, founding father of the controversial science of sociobiology, assures us that "all the tangible phenomena, from the birth of stars to the workings of social institutions, are based on material processes that are ultimately reducible, however long and tortuous the sequences, to the laws of physics" (Wilson 1998, p.5).

Likewise, the late Francis Crick tells us that, "while the whole may not be a simple sum of its parts, its behavior can, at least in principle, be *understood* from the nature and behavior of its parts *plus* the knowledge of how all these parts interact [italics in the original]" (Crick 1994, p. 11). On the other hand, many other scientists, like the great 20th century biologist Theodosius Dobzhansky, have appreciated that life involves something more than a successful chemistry experiment, or an energy-consuming "dissipative structure" analogous to a Bénard convection cell (in physicist Ilya Prigogine's monistic vision). As Dobzhansky (1970, p.3) truly noted:

> A man consists of some seven octillian (7×10^{27}) atoms, grouped in about ten trillion (10^{13}) cells. This agglomeration of cells and atoms has some astounding properties; it is alive, feels joy and suffering, discriminates between beauty and ugliness, and distinguishes good from evil. There are many other living agglomerations of atoms, belonging to at least two million, possibly twice that many biological species [or even several times more]....How has this come about?

What makes life something greater than the sum of its physical and chemical parts and gives living systems their remarkable emergent properties is attributable in part to the fact that it is a multi-level phenomenon and that new properties and even new principles arise at higher levels of "agglomeration" and organization, as the chemist Michael Polanyi (1968) and physicist Phillip Anderson (1972) argued compellingly in two landmark articles in the journal *Science* many years ago.

Equally important, the history of life on Earth has been an ongoing, creative undertaking. It reflects a very long history of "trial and success" in biologist Julian Huxley's characterization—that has been underway for perhaps four billion years. To be sure, there are many continuities in evolution (as Darwin himself first observed), and many ancient inventions that are still vitally important to sustaining life. But evolution is also a progressive process of becoming something more and different, although the process has also been punctuated with many challenges, many radical changes, and even dead ends.

But perhaps the most distinctive property of life, what distinguishes living systems from all of the other kinds of agglomerations in the natural world, is its dynamic goal-directedness. For life is a process with a purpose. Living systems have a vocation. They are not flotsam adrift in an all-powerful natural environment—"dependent variables" in the jargon of science. They are also partially "independent variables." They actively pursue survival and reproduction, and they do so by deploying an immense variety of different survival strategies in an immense number of different environments. As biologist Lynn Margulis and science writer Dorion Sagan put it in their 1995 book *What is Life?*, the global survival enterprise involves a "piling up of little purposes." In other words, living systems have an internally-defined teleology (or "teleonomy" in biologist Colin Pittendrigh's felicitous term).

This internal teleonomy, which humans have in common with all other living organisms (though our cultural cocoons sometimes insulate us from this reality), remains something of a "black box" for evolutionary biology. Biologists and social scientists have observed and documented its workings in a myriad of ways, from the foraging activities and choice-making decisions in colonies of bacteria to the skillful tool-using behaviors of our primate cousins and the transcendent cultural achievements of humankind. Indeed, what is most significant about the behavior of living organisms is their ability to make choices and to change – to adapt. Margulis and Sagan, allowing themselves a bit of poetic license, write: "At the most primordial level living seems to entail sensation, choosing, mind" (1995, p. 180). They call it "the sentient symphony."

Yet we still do not fully understand how this goal-directedness in life originated and evolved. Nor do we truly understand its mechanics. Where is the seat of life's unique purposiveness and how does it work? How is it able to organize and prioritize the functioning and the behavior of each living organism? Though the science of cybernetics, or feedback control theory, has shed much light on the matter, we still have much more to learn.

In addition to these well-known properties of living systems, there is another important but perhaps less appreciated attribute that should also be added to the list. Even the simplest forms of life embody a complex hierarchy of synergistic effects. Synergy, a ubiquitous phenomenon in the natural world, can be defined as *combined, or "co-operative" effects produced by two or more elements, parts, or individuals that are otherwise unattainable.* Synergy is often associated with the cliché "the whole is greater than the sum of its parts" (which dates back to Aristotle), but wholes are very often not greater than their parts—just different. A classic example is water, a liquid that results when two elemental gases are combined.

As I have discussed in detail elsewhere (Corning 1983, 2003, 2005), synergy represents one of the great governing principles of the natural world. It should properly rank right up there with such heavyweight concepts as gravity, energy, information and entropy as one of the keys to understanding how the world works. But more important, synergy has been greatly underrated as a source of creativity in evolution. It has been a major causal agency in the evolution of biological complexity. To paraphrase the novelist and polymath Arthur Koestler, true novelty occurs when things are put together for the first time that had been separate. In accordance with what I call the "Synergism Hypothesis," it is the functional effects produced by various forms of synergy in relation to the problems of survival and reproduction that have been responsible for the "progressive" evolution of complexity over time in living systems.

I hasten to add that the Synergism Hypothesis is fully consistent with Darwin's theory and with natural selection, but in contrast with various gene-centered theories (not to mention theories that posit some law-like progression or an internal self-making process in evolution), the Synergism Hypothesis is in effect an economic (or bioeconomic) theory of complexity. Synergy is always a contingent phenomenon in which the survival benefits must outweigh the costs. Another way of putting it is that synergies of various kinds are responsible for cooperation in the living world, not the other way around.

The role of synergy in evolution can most likely be traced back to the very origins of life. It is, in fact, an implicit premise underlying every one of the more or less formal hypotheses about the earliest steps in the evolutionary process, from Eigen and Schuster's (1977, 1979) hypercycles to Szathmáry and Demeter's (1987) stochastic corrector model, Wächtershäuser's (1988, 1990) surface (clay) metabolism model, the amphiphile (fatty molecule) "envelope" model (Deamer and Oro 1980, Morowitz et al., 1988) and the more recent speculations about the role of hydrothermal vents on the sea floor. All share the common assumption that cooperative interactions among various component elements and parts played a central role in catalyzing living systems.

DNA, the basic molecule of life, also utilizes synergy. Among other things, the double-stranded, antiparallel backbone, or scaffolding, of each giant DNA molecule hangs together only because there are covalent electron bonds that "glue" together the atoms of its constituent phosphate and deoxyribose molecules. By the same token, the vital role of DNA in biosynthesis is made possible by a highly coordinated division of labor (or, better said, a "combination of labor") between three different forms of RNA—the messenger RNA that makes copies of the relevant DNA sequence, the transfer RNA that assembles the appropriate amino acids, and the ribosomal RNA that lines up the amino acids in the proper order for assembling a protein.

Similarly, at the level of the genome, it goes without saying that genes do not act alone, even when major single-gene effects occur. An example is the so-called homeobox gene complex, which is responsible for defining the basic body plan for a wide range of organisms, from insects to humans. And the human genome sequencing project has established, among other things, that our genes are preeminently purveyors of cooperation and synergy production. For instance, there are some 1,195 distinctive genes associated with producing the human heart, 2,164 with our white blood cells and a staggering 3,195 with the human brain (Little 1995).

The origin of chromosomes, likewise, may have involved a co-operative/symbiotic process (see Maynard Smith and Szathmáry 1993). Sexual reproduction, one of the major outstanding puzzles in evolutionary theory, is also a cooperative phenomenon, as the term is used here. Although there is still great uncertainty about the precise nature of the benefits, it is assumed that sexual reproduction is, by and large, a mutually beneficial joint venture.

As we move up the scale of complexity, we find many other variations on the theme of functional cooperation and synergy. Once upon a time bacteria were considered to be mostly loners, but this is no longer the case. It is now recognized that large-scale, sophisticated cooperative efforts—complete with a division/combination of labor—are commonplace among bacteria and can be traced back at least to the origin of the so-called stromatolites (rocky mineral deposits) that were constructed by bacterial colonies some 3.5 billion years ago (Ben-Jacob et al. 1988; Shapiro 1988; Shapiro and Dworkin 1997; Margulis 1993). Shapiro suggests that bacterial colonies can be likened to multicellular organisms.

Complex eukaryotic cells (some as much as 10,000 times the size of a bacterium) can also be characterized as cooperative ventures—obligate federations that may have originated as symbiotic unions (parasitic, predatory or perhaps mutualistic) between ancient prokaryote hosts and what have now become cytoplasmic organelles, particularly the mitochondria, the chloroplasts and, possibly, eukaryotic undulipodia (cilia) and certain other internal structures that may have evolved from structurally-similar spirochete ancestors (Margulis 1993). Eukaryotes not only enjoy a sophisticated division/combination of labor but they also benefit from what I refer to as a synergy of scale. Each one can harbor many hundreds and sometimes even thousands of the energy-producing mitochondria, a vast source of power that bacteria do not enjoy.

Another whole new level of synergy in evolution was achieved with the appearance of multicellular organisms. Some insight into how this occurred is provided by the Volvocales, a primitive order of aquatic green algae that form tight-knit colonies. Volvocales have been popular with students of evolution ever since the 19th century, because their diverse members seem to mirror some of the various steps toward complex multicellular organization. The smallest of these species (*Gonium*) have only a handful of cells arranged in a disk, while the *Volvox* that give the Volvocale line its name may have some 60,000 cells in the shape of a hollow sphere that is easily visible to the naked eye. Each *Volvox* cell is independent, yet the colony-members collaborate closely. For instance, the entire colony is propelled by a "fur coat" of flagella whose coordinated efforts keep the sphere slowly spinning in the water.

The synergies achieved by *Volvox* were illuminated in a detailed study some years ago by the biologist Graham Bell (1985). Bell noted that the largest of the colonies have a division/combination of labor between a multicellular body and segregated reproductive cells. Bell's analyses suggested some of the benefits. Specialization facilitates growth (as Plato was the first to point out), which results in a much larger overall size. It also results in more efficient reproductive machinery (namely, a larger number of smaller germ cells). The large hollow enclosure in *Volvox* also allows the mother colonies to provide protected envelopes for their numerous daughter colonies; the offspring disperse only when the mother colony finally bursts apart.

But there is another vitally important collective benefit enjoyed by *Volvox*. Bell points out that their larger overall size results in a greater survival rate. It happens that these planktonic algae are subject to predation from filter feeders like the ubiquitous copepods, but there is an upper limit to the prey size that their predators can consume. Integrated, multicellular colonies are virtually immune from predation by filter feeders. It's another example of a synergy of scale.

Symbiosis between two or more different organisms – a commonplace occurrence in the natural world (as we now know)—added yet another new level of synergies to the superstructure of life. An example close to home involves the African honey guide, an unusual bird with a peculiar taste for beeswax (a substance that is more difficult to digest even than cellulose). In order to obtain beeswax, however, the honey guide must first locate a hive and then attract the attention of a co-conspirator, such as the African badger (or ratel). The reason is that the ratel has the ability to attack and dismember the hive, after which it will reward itself by eating the honey and leaving the wax behind for the birds. However, this unusual example of cooperative predation by two very different species depends upon a third co-conspirator. It happens that the honey guides cannot digest beeswax. They are aided by a symbiotic gut bacterium, which produces an enzyme that can break down wax molecules. So this improbable but synergistic feeding relationship is really triangular (Bonner 1988; Currie 2001).

What makes this example especially pertinent here is the fact that the honeyguides also form symbiotic/synergistic partnerships with humans, the nomadic Boran people of northern Kenya, with benefits for both partners that can be quantified. Biologists Hussein Isack and Hans-Ulrich Reyer (1989) conducted a systematic study of this behavior pattern some years ago and found that Boran honey hunting groups were approximately three times as efficient at finding bees' nests when they were guided by the birds. They required an average of 3.2 hours to locate the nest compared with 8.9 hours when they were unassisted. The benefit to the honey guides was even greater. An estimated 96% of the bees' nests that were discovered during the study would not have been accessible to the birds had the humans not used tools to pry them open.

We also marvel at the synergies that have been achieved by socially organized species, yet another distinct new level of cooperation (and synergy) in the natural world. As noted earlier, even bacterial colonies have exploited the benefits of sociality, but the apotheosis of this survival strategy has been achieved by much larger and more complex organisms. A popular example is the naked mole-rat, an African rodent species that lives in large underground colonies (usually numbering 75-80 but sometimes over 200). Mole-rats subsist by eating plant roots and succulent tubers. Affectionately dubbed "saber-toothed sausages" because they are hairless and have two outsize front teeth for digging, naked mole-rats are a particularly significant example of a division/combination of labor in mammals. In fact, these odd-looking animals utilize specialized worker "castes" and a pattern of breeding restrictions that is highly suggestive of the social insects.

Typically (but not always), the breeding is done by a single "queen", with other reproductively suppressed females waiting in the wings. The smallest of the non-breeders, both males and females, engage cooperatively in tunnel-digging, tunnel-cleaning and nest-making, as well as transporting the colony's pups, foraging for food and hauling the booty back to strategic locations within the colony's extensive tunnel system. (One investigator found a mole-rat "city" in Kenya that totaled about two miles of underground tunnels and occupied an area equivalent to 20 football fields.) On the other hand, the vital and dangerous role of defense in a mole-rat colony is allocated to the largest colony members, who respond to intruders like predatory snakes by trying to kill or bury them and/or by sealing off the tunnel system to protect the colony. The mole-rat "militia" will also mobilize for defense against intruders from other colonies.

Why do mole-rats utilize this highly cooperative survival strategy? Biologist Paul Sherman and his co-workers, who have studied these animals extensively, provide a bioeconomic explanation: "We hypothesize that naked mole-rats live in groups because of several ecological factors. The harsh environment, patchy food distribution and the difficulty of burrowing when the soil is dry and hard, as well as intense predation, make dispersal and independent breeding almost impossible. By cooperating to build, maintain and defend a food-rich subterranean fortress, each mole-rat enhances its own survival" (Sherman et al., 1992, p. 78). (Although it is not stressed in the mole-rat research literature, another critically important facilitator is a cooperative relationship between the mole-rats and a bacterial symbiont that can break down the cellulose in succulent tubers.) In other words, the mole-rats' survival strategy is ultimately based on the many synergies they achieve.

By many different criteria, the numerous functional relationships that exist in nature between animals and various "tools" also constitute a form of symbiosis and represent yet another distinct level of synergy in evolution. For animal-tool interactions can produce many otherwise unattainable cooperative effects that can spell the difference between life and death. As Edward Wilson pointed out in his comprehensive 1975 synthesis, *Sociobiology*, tools provide a means for quantum jumps in behavioral invention, and in the ability of living organisms to manipulate their environments.

Thus, some birds use rocks to break open egg shells while others deploy thorns to dig for grubs under the bark of trees. Some chimpanzees use "wands" to fish for buried insects while others use stone anvils and hammers to crack open the proverbial tough nuts. California sea otters are legendary for using rocks that rest on their bellies while they float on their backs as a tool for breaking open mussels and other hard-shelled prey.

Elephants are especially impressive tool-users. Among other things, they scratch or clean their ear cavities with grass or other vegetation; they scratch their bodies with sticks held in their trunks; they wipe cuts with clumps of grass held in their trunks; they reach toward inaccessible food and hit humans with sticks held in their trunks; they throw objects at other animals with great accuracy, including humans and their vehicles; they brandish or wave branches, apparently to chase away flies or to threaten other animals; they lay mats of grass over their backs to keep biting flies away; they may pile up branches or push a large tree down onto a fence, forcing it to sag so that they can walk over it; they even use sticks and stones for making spontaneous "drawings" in the dirt (Wilson 1975, Chevalier-Skolnikoff and Liska 1993). In short, animal-tool symbiosis is widespread in nature, and the difference between humans and other tool-using species, as Darwin noted, is a matter of degree; there is no difference in kind.

Nevertheless, it can also be argued that humankind has achieved the highest level of behavioral synergy in evolution by virtue of the fact that we have added an entirely new cultural/technological dimension to the process. To be sure, we benefit from all of the other levels of synergy that exist in living systems, but we also do something more. We combine new and more powerful methods of obtaining, storing and transmitting information with an ongoing, cumulative process of tool and technology invention. These superlative human skills, the roots of which probably trace back several million years in our ancestry, very likely were "pacemakers" that shaped the trajectory of our biological evolution. In biologist Jonathan Kingdon's (1993) characterization, we are the "self-made man." (A detailed discussion of this hypothesis can be found in Corning 2003.) From our earliest stone tools to the control of fire (and other exogenous energy sources) to language, writing and the latest in interplanetary space technologies, humankind has invented new and increasingly complex technological synergies that have also expanded the scope and reach of the evolutionary process itself. We represent a synergy of synergies.

Consider just one example, a commonplace consumer product like an automobile. Actually, an automobile is a technological wonder that our not-so-remote ancestors of, say, 200 years ago would surely have marveled at. It represents an assemblage of (depending on the car and how you count) some 15-20,000 precisely designed and manufactured parts, comprised of some 60 different materials. It also embodies many different technologies, from metallurgy to weaving, glass-making, ceramics, hydraulics, rubber-vulcanizing, electricity, paints, plastics, and the latest in electronics. And it incorporates literally thousands of different human inventions: threaded screws, articulated gears, springs, hinges, clamps, cotter pins, bolts, chains, filters, locks, lock washers, Velcro fasteners, ball bearings, fans, pumps, valves, storage batteries, electric motors and, of course, internal combustion engines.

Furthermore, the synergy produced by these self-propelled machines will occur only if all, or almost all, of the parts work together harmoniously. Most of us are oblivious to how the fuel injectors, timing belts, intake valves, exhaust manifolds and a plethora of other parts "co-operate"; we notice only a few of the details and pay close attention only when something malfunctions. In fact, one test for the presence of synergy is that the "whole" may not work if a major part is removed or breaks down—a wheel, the alternator, the ignition key, or the driver for that matter. (As an aside, this method of testing for synergy was originally suggested by Aristotle over 2300 years ago in his classic study of first principles, later renamed the *Metaphysics*.)

An automobile also represents something truly novel in the history of life on Earth, if not in the universe. It is inexplicable in terms of the laws of physics, or the dynamical attractors of chaos theory, or the quarks of quantum theory, or even the laws of thermodynamics—although each of these disciplines has something useful to say about automobiles and how they work. Equally important, you cannot "explain" an automobile simply by listing all of its parts. Nor can you throw all of those parts into a disorganized heap and still get the synergy. It takes a very particular arrangement of the parts to make the magic happen.

So what can we conclude? Life is a phenomenon that has a great many distinctive properties, but many of these in turn are the result of a very long process of invention – of "tinkering" rather than a pre-planned "engineering" project, as the Nobel biologist François Jacob (1977) put it in a much-quoted article in *Science*. Life, as we observe it and live it, can also be defined in terms of what it is able to do, and what it does. By that definition, the very nature of life has progressively expanded and become more enriched over time with new capabilities – and new synergies.

So the final answer to that provocative question, "What is Life?" is that it is still evolving, still creating itself, still exploring its potentialities and still discovering new forms of synergy, along with addressing many ongoing challenges and coping with new threats. And, as always, the outcome remains to be seen. Teilhard de Chardin (1959) observed that in humankind evolution has become conscious of itself. With that knowledge, and with our ever-expanding cultural/technological powers, we have the opportunity to further enlarge the definition of life. Indeed, we have the power to consciously influence the future course of evolution (as we have done unwittingly already). We can only hope that we will choose our course wisely. To paraphrase Dobzhansky once again, the future is not vouchsafed by any law of nature, but it may be striven for.

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